Silicon-Film™ Sheet, Solar Cell and Module Manufacturing

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ABSTRACT

Advances in solar cell manufacturing systems for large-area Silicon-Film™ polycrystalline silicon sheet material are reviewed. Recent progress in continuous rapid thermal junction diffusion and cassette-less wet chemical processing is discussed. A single Silicon-Film™ sheet generation system operating at 3.1 m/min now has a capacity of 15 MW of silicon sheet per year. This sheet generation system is used as the basis for an advanced single-thread production line design for manufacturing the next generation of Silicon-Film™ solar cells whose area is nominally 400 cm^2. These solar cells are being used to design large-area solar modules that can produce up to 220 W of power. Custom module designs have been developed for AstroPower's domestic on-grid rooftop system programs.

1. Introduction

Silicon-Film™ solar cells are the low-cost solution for solar electric power generation. The PVMaT program has been, and continues to be, critical to the success of Silicon-Film™ solar cells and modules. Silicon-Film™ production systems generate sheets of polycrystalline silicon in a continuous in-line process. The sheet making system has now evolved through five design generations, and a single system is capable of producing 15 MW of polycrystalline silicon sheet per year.

Many potentially high-volume solar cell processes have been limited by batch processing and by handling issues. Batched wet chemical processes require wafers to be loaded into plastic cassettes. These cassettes reduce process throughput and yield, increase handling costs, and ultimately limit the process to only one wafer size. Junction diffusion in conventional tube furnaces is limited by the diameter of the process tubes where uniformity, throughput and yield suffer as the wafer area increases.

One solution to increasing solar cell manufacturing volume has been to develop paralleled processes handling larger numbers of smaller-area wafers. By taking advantage of the recent progress in large-area Silicon-Film™ sheet generation and in advanced solar cell process systems that eliminate handling issues and bottlenecks in high temperature and wet processes, it is also possible to design a high-volume solar cell production line with only a single-thread serialized process systems rather than many paralleled operations.

A standardized grid-connected PV system has been developed and targeted to the residential market. This program has the goal of mainstreaming solar electric power onto the US market.

2. Silicon-Film™ Solar Cell Manufacturing

AstroPower's solar cell manufacturing systems have advanced along a critical path beginning with processes that have the most impact on throughput [1]. This effort began with the development of the polycrystalline Silicon-Film™ sheet material for the starting wafers. As the dimensions of the sheet and wafer increased, the junction diffusion process that took place in large-diameter tube furnaces became the volume limiter. Development of continuous high temperature processing for impurity gettering and for junction diffusion followed. Volume increases in wet chemical processes were not limited by the larger wafer area, but instead by weight and handling considerations. The replacement of batch processing with in-line, continuous wet chemical process systems have paved the way to complete elimination of cassettes from the production line. Process system development in each of these areas is discussed in more detail below.

In 1998 AstroPower began manufacturing AP-225 Silicon-Film™ solar cells (240 cm^2 area) in the Pencader facility. Since then the Pencader plant has expanded to 12,000 m^2 (130,000 ft^2), twice its original size, and now produces the new APx-8 Silicon-Film™ solar cell (nominally 400 cm^2) as well as single-crystal solar cells manufactured from recycled wafers procured from the integrated circuit industry.

3. Silicon-Film™ Cell Process Overview

Table I shows a summary of the AP-225 cell process sequence (circa 1997) compared to a 15-MW single-thread production line that is being developed for producing APx-8 solar cells.

Production systems for the AP-225 solar cell were based on handling 25-wafer cassettes, small batch processes, and limited throughput. The batch process sequence contained 24 discrete operations, and nine places where the wafers were either loaded or unloaded from cassettes or boats. The cassettes performed two functions: in batch-type wet processing cassettes are required for handling wafers in the solution tanks. In the dry processes, such as contact printing, cassettes are used between stations to move batches and to protect the junction. Once the contact firing operation is completed, the cells were handled as coinstacks in magazines.

The advanced APx-8 solar cell process sequence in Table I contains 11 discrete operations, and no cassette handling steps. The goal of eliminating cassettes is accomplished on the APx-8 single-thread production line by using conveyorized process equipment in all wet chemical and high-temperature steps. Several previously discrete processes are combined, such as at contact metallization where the back and front contacts are printed and fired on one unbroken sequence. Wafers are transferred between stations, such as between print-fire and test-sort, by coinstacking magazines. In these ways the process sequence is simplified and the amount of handling is reduced.

Table 1. Comparison of solar cell manufacturing sequences for AP- 225 (circa 1997, 24 process steps) and larger-area APx-8 Silicon-Film™ solar cells (11 process steps).

AP-225, 225 cm^2	APx-8, 240 cm^2
Fabricate sheet	Fabricate sheet
Size wafer	Size wafer
Pre-getter preparation	Pre-getter preparation
Getter anneal	Getter anneal
Load into cassette Etch surface	In-line surface etch
Unload from cassette Diffuse in tube furnace Unload from boat	In-line junction diffusion
Isolate junction	Isolate junction
Load into cassette Etch diffusion oxide	In-line diffusion oxide etch
	AR coat with PECVD SiN
Unload from cassette Print/dry back busbars Load into cassette	Print and co-fire metal contacts
Unload from cassette Print/fire back Al field Load into cassette	
Unload from cassette	
Print/fire front contacts	
AR coat with TiOx	
Burnish busbars	
Test and sort	Test, sort and inspect
Inspect	

4. Silicon-Film™ Sheet Formation

Silicon-Film™ production systems generate low-cost sheets of polycrystalline silicon in a continuous in-line process. The equipment, materials, and processes have been under development at AstroPower for over ten years. Each successive generation of Silicon-Film™ sheet generation system brought increases in throughput, both through sheet width and sheet growth speed. The present system has a nominal 20-cm sheet width and operates at 3.1 meters per minute. With its higher growth speed and increased width, the SF5 sheet system has a capacity of 15 MW per year.

The SF5 sheet system was specifically designed to produce the larger-area APx-8 Silicon-Film™ solar cells. Figure 1 shows the APx-8 solar cell compared to the AP-225 solar cell. The new APx-8 solar cells are nominally 20 cm on a side, once again setting a new standard for polycrystalline solar cell area and power. This new solar cell is more than four times larger than the typical polycrystalline silicon solar cell produced ten years ago.

Figure 1. APx-8 Silicon-Film™ solar cell compared to previous generation AP-225. The active area is 80% greater.

5. High Temperature Wafer Processing

For optimum performance, screen-printed contact metallizations on silicon solar cells must be sintered at high temperature for very short times. The temperature-time "spike" profile is most conveniently obtained by using halogen-lamp infrared (IR) belt furnaces operating with high belt speeds. Although a wafer may not reach thermal equilibrium, the silicon surface temperatures change at very high rates due to the interaction between the wafer and the IR heating source. Contact firing processes in the Pencader facility are based on 90-cm wide IR belt furnaces. At very modest belt speeds a contact process system based on these furnaces has a process capacity of more than 1,000 APx-8 wafers per hour, with additional capacity at higher belt speeds.

While contact firing requires rapid heating and cooling, rapid diffusion processes require a tightly controlled cooling rate. Although the process is more complicated, rapid IR heating has been used to produce high-performance diffused junctions on both single-crystal and polycrystalline silicon solar cells [2,3,4]. Conventional tube diffusion processes have limited solar cell area, uniformity, and throughput. Muffle-type belt furnace diffusion suffers from throughput limits. The advantages of a rapid thermal diffusion are unlimited area, consistent uniformity, and high throughput. In 1997 AstroPower developed under the PVMaT program a production-level in-line junction diffusion and impurity gettering processes for Silicon-Film™ wafers that are based on 90-cm wide halogen-lamp belt furnaces. The rapid diffusion process uses a low-cost phosphorus-based liquid dopant source that is non-hazardous and stable, and produces uniform junctions on any size wafer in just a few minutes. The IR furnace belt speed is approximately 100 cm/min and the belt accommodates four APx-8 wafers across its width. The throughput of the rapid thermal diffusion process is greater than 1,000 Silicon-Film™ wafers per hour.

6. In-line Wet Chemical Wafer Processing

Several wet chemical process steps, including surface preparation prior to junction diffusion and oxide etching following diffusion, are critical components of the silicon solar cell manufacturing sequence. A tank-based batch chemical process requires wafers to be loaded into cassettes that maintain wafer separation in the solution. The tight wafer spacing within cassettes reduces the liquid flow to the wafer surfaces and results in uneven etching or cleaning at the edges where the wafers contact the cassettes.

Development of cassette-less in-line wet chemical processing systems eliminates many of these limitations. An in-line system is capable of handling wafers of various sizes, and even meter-long Silicon-Film™ sheets. Operator exposure to chemicals is eliminated since the process chemicals are completely enclosed -- dry wafers are loaded into the chemical process system, and completely rinsed and dried wafers are unloaded from the system. The composition of the solutions is maintained within operating limits by in-line monitoring and control, which reduces material usage and waste stream volume. The throughput of an in-line chemical system is not limited by tank size or by cassette load-unload operations. Total processing time is further reduced and process quality is improved by the more efficient cassette-less rinsing and drying steps.

The handling advantages of continuous in-line wet chemical processing were demonstrated under the PVMaT program by developing in-line process systems for rinser-dryer operations and for diffusion oxide etching (prior to contact printing) using dilute hydrofluoric (HF) acid solution.

Safety issues regarding the HF oxide etch solution were a significant concern in the design of the in-line diffusion oxide etch system. As a result, the system was designed for immersion etching rather than vapor etching. The HF solution then remains as a dilute room temperature solution.

At a conveyor transport speed of approximately 100 cm/min, the system has an annual APx-8 solar cell capacity of more than 15 MW. With PVMaT support, this system successfully met aggressive material and labor cost reduction goals by reducing HF acid usage and disposal costs, by reducing DI water consumption, and by completely eliminating labor costs for cassette loading and unloading that are required by the previous batch-based diffusion oxide etch process.

The Silicon-Film™ surface etch process is based on a heated caustic solution. The critical parameters for the silicon surface etch process are solution temperature, which strongly influences the silicon etch rate, and solution composition, which impacts surface quality. It is also critical that the surface etching action be terminated quickly. As a batch process, the quality of the surface etch process is highly dependent on the performance of the process operator who will move the cassettes from tank to tank, just as it is sensitive to the etch solution concentration and temperature.

In a batch etching system the wafer edges are masked by the cassette slots which reduces the etching and rinsing action and results in process defects on the wafer surface. An in-line surface etch system utilizes a wheeled wafer transport system that minimizes contact to the surfaces of the wafer. By eliminating the cassettes, large-area wafers and even Silicon-Film™ sheets can be processed by the same equipment with virtually no need for fixturing and with no edge masking defects. Under the PVMaT program, two prototype systems have been built and evaluated, and a production system is now been fabricated.

7. 15-MW/year Solar Cell Production Line Design

Developments such as those described above are used to design a single-thread production line with an annual capacity of 15 MW of APx-8 Silicon-Film™ solar cells. A schematic of the 15-MW single-threaded production line is shown in Figure 2.

The throughput of the line is governed by the initial sheet formation step. Each of the subsequent solar cells processes exceeds the capacity rating of the Silicon-Film™ sheet generation system and operates asynchronously. No cassettes are used in this manufacturing system design. However, some of the transfer operations take place using coinstack magazines. The individual process stations are interconnected using pallet-style conveyors for the magazines.

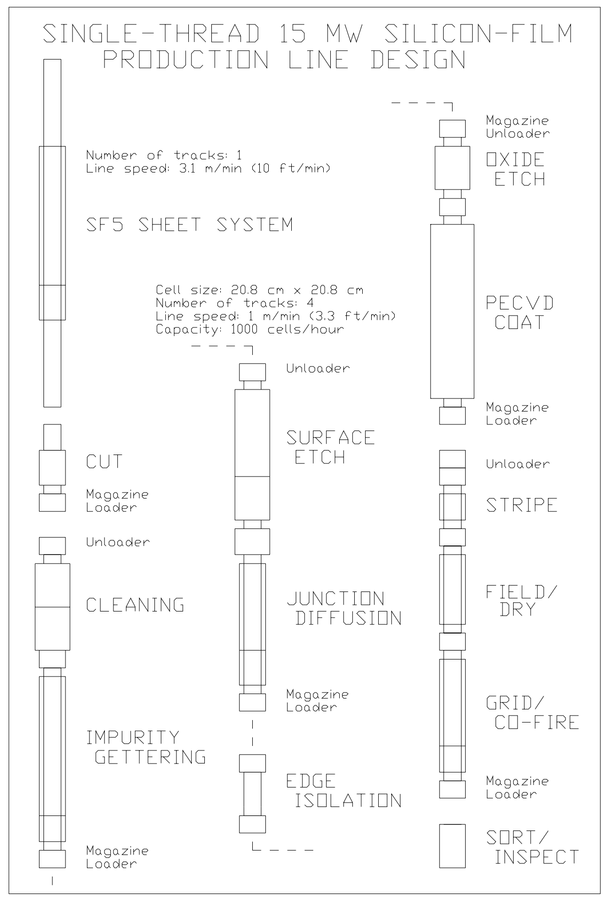

Figure 2. Plan view of solar cell manufacturing system with a capacity of 15 MW for Silicon-Film™ sheet material.

8. Roof-top Systems

In 1997, AstroPower introduced a line of fully pre-packaged grid-connected PV systems principally for the residential market. The goal of the program is to mainstream solar electric power into the US market. Our SunUPS® and SunLine™ systems represent a significant step forward in the development of markets for grid-connected PV. Important features of the SunUPS and SunLine systems include:

- Several key innovations related to system mounting and module wiring that dramatically reduce installation time and total installed costs;
- Standardization and packaging which eliminates the need for custom design of each system and procurement of components from a variety of sources;
- Integrated system design that addresses utility interconnection and building code requirements; and
- Exceptional documentation and technical support.

AstroPower is actively marketing these systems in target U.S. markets. AstroPower is teaming up with some of the leading US homebuilders to integrate solar power in new construction, and we have formed a partnership with a leading national brand retailer to make solar power systems easy to get in the retrofit market.

Figure 3. AstroPower SunChoice Home Power System

9. Conclusions

Silicon-Film™ production systems generate low-cost sheets of polycrystalline silicon in a continuous in-line process. The fifth generation of Silicon-Film™ sheet generation system is presently in use and operates at 3.1 meters per minute with a capacity of 15 MW per year. This Silicon-Film™ sheet generation system is the basis for an advanced single-thread solar cell production line design that utilizes processes and equipment specifically developed for high-volume production of large-area solar cells. Key areas for improvement that have been addressed are continuous high temperature processing and in-line wet chemical processing.

AstroPower has developed production-level in-line junction diffusion and impurity gettering processes for Silicon-Film™ wafers and sheet material that are based on 90-cm wide halogen-lamp (IR) belt furnaces. The diffusion process utilizes a phosphorus-based liquid dopant source that is low-cost, non-hazardous, and stable.

AstroPower has developed cassette-less in-line diffusion oxide etching systems that have significantly increased the safety, reduced the cost, and improved the drying quality of the diffusion oxide etch process. A cassette-less in-line wet chemical process system for surface etching was developed, and a high-volume surface etching system for volume production is now being fabricated.

High-throughput in-line systems for PECVD antireflection coating and hydrogen passivation and for contact metallization are being developed to complete the Silicon-Film™ solar cell production line equipment set.

Recent advances in large-area wafer handling and processing have been used to design a single-thread production line with an annual capacity of 15 MW of APx-8 Silicon-Film™ solar cells. Several previously discrete process steps have been combined, and wafers are transferred between stations by magazines instead of cassettes. These changes have reduced the number of discrete process steps by more than a factor of two.

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